

SDSS, LSST AND GAIA: LESSONS AND SYNERGIES

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Abstract. The advent of deep, wide, accurate, digital photometric surveys exemplified by the Sloan Digital Sky Survey (SDSS) has had a profound impact on studies of the Milky Way. In the past decade, we have transitioned from a scarcity to an (over)abundance of precise, well calibrated, observations of stars over a large fraction of the Galaxy. The avalanche of data will continue throughout this decade, culminating with Gaia and LSST. This new reality will necessitate changes in methodology, habits, and expectations both on the side of the large survey projects as well as the astrophysics community at large. We argue, based on the experience with SDSS, that surveys should release data as early and often as possible incorporating incremental improvements in each subsequent release, as opposed to holding off for a single, big, final release. The scientific community will need to reciprocate by performing analyses and (re-analyses) appropriate to the current fidelity of the released data, understanding that these are continually evolving and improving products.

1 Introduction

In the past decade, the data from the Sloan Digital Sky Survey (SDSS) have dramatically enhanced our picture of the Milky Way. This includes comprehensive Galactic structure studies (e.g. Carollo et al., 2007; Jurić et al., 2008; Ivezić et al., 2008a; Bond et al., 2010), discoveries of overdensities and tidal streams (e.g. Newberg et al., 2002; Belokurov et al., 2006; Jurić et al., 2008) as well as discoveries of a significant population of ultra faint Milky Way satellites (e.g. Willman et al., 2005; Belokurov et al., 2007, and others). An example from Jurić et al. (2008) given in Figure 1 shows a detection of two low-contrast disk overdensities in stellar number density maps constructed from SDSS observations of ~ 48 million stars.

The SDSS is a digital photometric and spectroscopic survey. It has covered a contiguous region of about $7,600 \text{ deg}^2$ centered on the North Galactic cap, a

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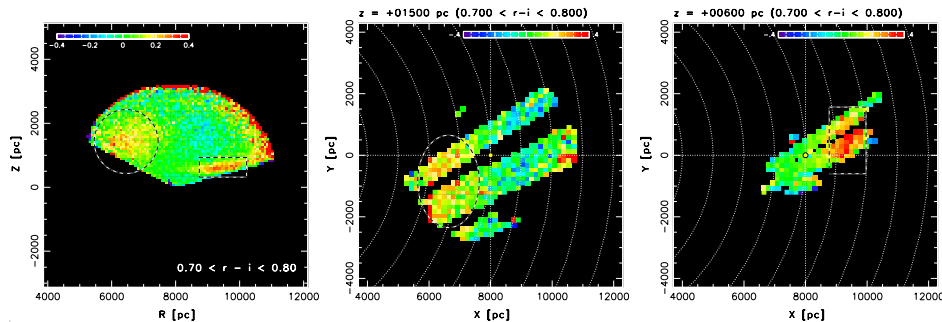


Fig. 1. Two low-contrast disk overdensities detected in SDSS DR3 stellar number density map residuals. The left panel shows the $Data/Model - 1$ residuals in the (R, Z) plane, while the center and left panels show the $X - Y$ cross sections intersecting the detected overdensities. See Jurić et al. (2008) for details.

smaller but deeper area in the Galactic South ($\sim 225 \text{ deg}^2$), and approximately $3,200 \text{ deg}^2$ of imaging for the Sloan Extension for Galactic Understanding and Exploration (SEGUE). More generally, it is an example of the kind of deep, wide and accurate surveys that will be increasingly common in this decade. A non-exhaustive list includes Pan-STARRS PS1 (Kaiser et al., 2002) that has already surpassed the SDSS in terms of covered area in less than 6 months after the start of its science mission, SkyMapper (Keller et al. 2005), currently in commissioning, the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST; Su et al., 1998), the Dark Energy Survey (DES; Flaugher, et al., 2005), and of course Gaia (Perryman et al., 2001) and LSST (Tyson, 2002; Ivezić et al., 2008b).

All these, including Gaia, share the common thread of aiming to produce and publish large ($> 10^8$ objects) and wide area datasets, a challenge the SDSS has already faced and successfully tackled.

2 Publishing and Consuming Large Datasets: Early, Often, Iterate

The lessons learned from SDSS are many. Here we limit ourselves to only two specific areas of immediate interest to Gaia and its users: deciding when and what to publish, and appropriately approaching the published data.

2.1 Release Early, Release Often

The SDSS has published the first public release of its data (the “Early Data Release”; EDR) in June 2001 (Stoughton et al., 2002). It consisted of roughly 460 deg^2 of imaging data, 54,000 follow-up spectra (about 5% of the planned totals) and a photometric and astrometric catalog of ~ 14 million objects.

By today’s SDSS Collaboration standards, the data included in this release would be considered substandard, even embarrassing. To illustrate this point,

at the time of the EDR even the true filter bandpasses were not known, the photometric calibration was at 3-5% level (as opposed to current $\sim 1 - 2\%$), and the output formats and tables in the data distribution system were far from being finalized.

In spite of these deficiencies, the EDR was a major success (and never criticized as premature). First, it demonstrated that the survey was collecting and processing data (an important milestone for a project 10 years in the making). Secondly, the release generated invaluable feedback from the community which was incorporated into, and significantly strengthened the subsequent data releases. Most importantly, the data described in the EDR produced substantial scientific returns, including (of importance to Galactic astronomy) the discovery of the Monoceros Stream (Newberg et al., 2002). At the time of writing of this contribution, the EDR paper has been cited 1215 times.

The SDSS has continued with releases on a 12-18 month schedule, with the latest (8th) data release planned for December 2010. Besides adding more area, every new release involves reprocessing of *all previously published data* to correct problems identified in the older releases, as well as to benefit from major improvements in the processing software (for example, the inclusion of an improved photometric calibration algorithm; Padmanabhan et al., 2008). In SDSS experience, many of the problems reported by users were very subtle and practically the only way to discover them was to perform “cutting-edge” science analysis and then critically examine the results.

The SDSS is far from alone in this approach. The RAVE survey (Zwitter et al., 2008), as well as UKIDSS (Lawrence et al., 2007), follow the same strategy. The planned Large Synoptic Survey Telescope (LSST) will follow a similar yearly release schedule. This “release early, release often” approach is also well known in open source software development (Raymond, 1997). The early data releases result in better communication and feedback from the wider astrophysical community, improve the quality of the published datasets, and reduce the overall “time to science”.

We feel the same model is applicable to Gaia. In addition to helping the Gaia project team discover and correct problems as they appear, early releases will surely generate a significant amount of follow-up science, enable synergies with ground based surveys such as LSST (see Section 3), as well as benefit the project in terms of education and public outreach.

2.2 Understanding that Datasets Evolve

The paradigm described above puts an important onus of responsibility on the users to take into account the evolving nature of the datasets. As will be noted elsewhere in this volume (see the contribution by Hogg), the only “final” product a survey can ever deliver are the *raw images*. Everything else, including the catalogs, is a *derived product* and subject to change as the understanding of the instrument, the processing algorithms, or the underlying assumptions (priors) evolve. To the best of our knowledge, no survey ever had all of these requirements well known

early. However, the benefits of the early and regular access to data as they are collected by far outweigh difficulties associated with evolving datasets.

The end users need to be aware of these caveats, especially when making use of the early data releases that will not have the full quality and reliability traditionally expected from a published catalog. Of course, while certainly a potential source of frustration, good understanding of (any!) dataset and its limits significantly improves the quality and longevity of the resulting science. Again, early and frequent data releases not only help users to understand “the survey error bars”, but perhaps more importantly help the project team to improve them before it is too late to “fix the problem”.

3 The Galaxy with LSST and Gaia

The Large Synoptic Survey Telescope, (LSST; Ivezić et al., 2008b), will be a large, wide-field ground-based system designed to obtain multiple images covering the sky visible from its location at Cerro Pachón, Chile. The current baseline design, with an 8.4m (6.7m effective) primary mirror, a 9.6 deg² field of view, and a 3,200 Megapixel camera, will allow about 10,000 square degrees of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average. The survey area will include 30,000 deg² with $\delta < +34.5^\circ$, and will be imaged multiple times in six bands, *ugrizy*, covering the wavelength range 320–1050 nm. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will observe a 20,000 deg² region about 1000 times in six bands during anticipated 10 years of operations. These data will result in databases including about 20 billion objects.

LSST will produce a massive and exquisitely accurate photometric and astrometric dataset for about 10 billion Milky Way stars. The coverage of the Galactic plane will yield data for numerous star-forming regions, and the *y* band data will penetrate through the interstellar dust layer. Photometric metallicity measurements will be available for about 200 million main-sequence F/G stars which will sample the halo to distances of 100 kpc (Ivezić et al., 2008a). No other existing or planned survey will provide such a massive and powerful dataset to study the outer halo (including Gaia which is flux limited at $r = 20$, and Pan-STARRS which will not have the *u* band). The LSST in its standard surveying mode will be able to detect RR Lyrae and classical novae out to 400 kpc, and hence explore the extent and structure of the halo out to half the distance to M31. All together, the LSST will enable studies of the stellar distribution beyond the presumed edge of the Galactic halo, of their metallicity distribution throughout most of the halo, and of their kinematics beyond the thick disk/halo boundary (LSST Science Collaborations et al., 2009).

In the context of Gaia, the LSST can be thought of as its deep complement. A comparison of LSST and Gaia performance is given in Figure 2. Gaia will provide an all-sky catalog with unsurpassed trigonometric parallax, proper motion and photometric measurements to $r \sim 20$ for about 10^9 stars. LSST will extend this map to $r \sim 27$ over half of the sky, detecting about 10^{10} stars. Because of Gaia’s

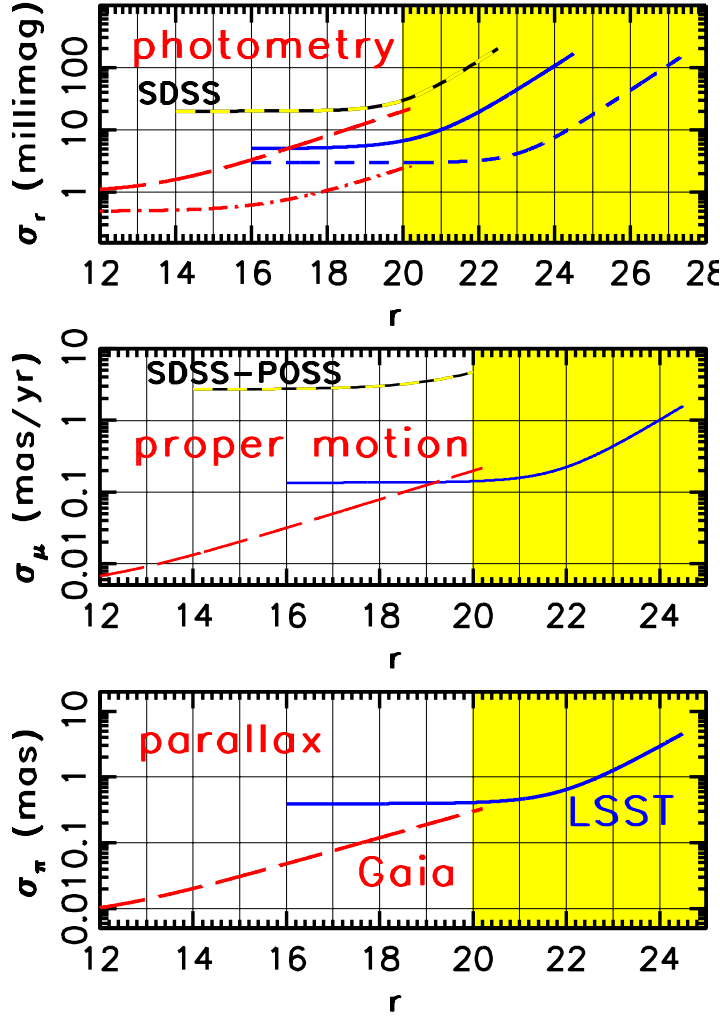


Fig. 2. A comparison of photometric, proper motion and parallax errors for SDSS, Gaia and LSST, as a function of apparent magnitude r , for a G2V star (it is assumed that $r = G$, where G is the Gaia’s broad-band magnitude). In the top panel, the curve marked “SDSS” corresponds to a single SDSS observation. The red curves correspond to Gaia; the long-dashed curve shows a single *transit* accuracy, and the dot-dashed curve the end of mission accuracy (assuming 70 transits). The blue curves correspond to LSST; the solid curve shows a single *visit* accuracy, and the short-dashed curve shows accuracy for co-added data (assuming 230 visits in the r band). The curve marked “SDSS-POSS” in the middle panel shows accuracy delivered by the proper motion catalog of Munn et al. (2004). In the middle and bottom panels, the long-dashed curves correspond to Gaia, and the solid curves to LSST. Note that LSST will smoothly extend Gaia’s error vs. magnitude curves four magnitudes fainter. The assumptions used in these computations are described in Eyer et al. (in prep.).

superb astrometric and photometric quality, and LSST’s significantly deeper reach, the two surveys are highly complementary: Gaia will map the Milky Way’s disk with unprecedented detail, and LSST will extend this map all the way to the halo edge (Eyer et al., in prep).

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